APPLICATION

FOR

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TITLE: **INFRASTRUCTURE-INDEPENDENT DEEPWATER OIL FIELD DEVELOPMENT CONCEPT**

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INFRASTRUCTURE-INDEPENDENT DEEPWATER OIL FIELD DEVELOPMENT CONCEPT

Cross-reference to related applications

This is a continuation-in-part of Application Serial No. 09/818,117 filed on March 27, 2001, and assigned to the assignee of the present invention. That application is hereby incorporated by reference in its entirety.

Background of Invention

Field of the Invention

[0001] The invention relates generally to offshore oil and gas production and transportation.

Background Art

[0002] A major factor in determining whether to exploit an offshore oil and gas field is the feasibility of handling and transporting the hydrocarbons to market once they are produced. Generally, hydrocarbons produced offshore must be transported to land-based facilities for subsequent processing and distribution. Temporary storage may be provided at the offshore production site for holding limited quantities of hydrocarbons produced and awaiting transport to shore. In some cases, equipment is also provided at the offshore production site for separating and/or treating the produced hydrocarbons prior to storing and transporting them to shore.

[0003] In the case of an offshore production facility located relatively close to shore, hydrocarbons (*i.e.*, oil and/or natural gas) produced may be feasibly

transported to shore through a pipeline system extending from the offshore site (*e.g.*, offshore platform or sub-sea wells) to the shore along the ocean floor or seabed. This type of pipeline system is typically preferred, when feasible, because it permits the constant flow of hydrocarbons to shore regardless of the weather or other adverse conditions. However, in some parts of the world, the use of a seabed pipeline system for transporting hydrocarbons to shore may not be economically feasible.

[0004] For offshore facilities located a great distance from shore, construction of a pipeline to shore is typically not practicable. In these cases, floating vessels, known as tankers, are used to transport hydrocarbons to shore. Tankers are specially designed vessels, which have liquid hydrocarbon storage (or holding) facilities, typically, in the hull of the vessel. In the case of crude oil production, natural gas, water, and other impurities are typically removed from the oil prior to offloading the oil onto tankers for transport.

[0005] Because tankers float on the water surface, their operations are largely dependent upon surface conditions, such as wind, wave, and current conditions. Thus, tankers are typically not operated during severe or unfavorable conditions. Additionally, operation of a particular tanker may be interrupted periodically for maintenance and repairs. Due to the large expense associated with maintaining tankers, tankers may also be shared among several offshore sites. As a result, long delay periods may occur between tanker availability for a particular site. Therefore, it is desirable to have storage facilities available at the offshore site to avoid the need to "shut-in" (or halt) production due to tanker unavailability. Additionally, offshore storage may be desired to allow for continuous production operations, independent of tanker hook-up and disconnect operations, as discussed below.

[0006] Examples of existing offshore production and storage systems used for deepwater applications are illustrated in Figure 1 and in Figures 2A-2D. Figure 1 shows one example of a production platform **2** used in a deepwater application. This production platform **2** includes processing and storage equipment **4** for separating and treating crude oil collected from platform wells 5 and sub-sea wells **6** and storing a limited quantity of the processed oil when transport is not available. Because the surface area and weight carrying capacity of the production platform **2** is extremely limited, storage facilities provided on a platform **2** are limited in size and, thus, inadequate for handling large quantities of hydrocarbons which may be produced during periods of shuttle tanker or other hydrocarbon transport unavailability.

[0007] Figure 2A shows a floating production, storage, and offloading (FPSO) system **10**, which comprises an FPSO tanker **11** specially equipped to function as an offshore production facility. The FPSO tanker **11** is permanently moored at the offshore site and connects to the sub-sea wells or sub-sea production gathering system **14** through one or more flowlines **18** connected to the production inlet **16** of the FPSO tanker **11**. During production operations, produced hydrocarbons are received, directly or indirectly, from the sub-sea wells **14**. Once on the FPSO tanker **11**, hydrocarbons are processed and temporarily stored. Hydrocarbons stored on the FPSO tanker **11** are periodically transferred onto a shuttle tanker **12** temporarily positioned in the vicinity of the FPSO tanker **11** during the transfer.

[0008] Figure 2B shows one example of a floating storage and offloading (FSO) system **20**, which is a pure form of ship-based storage without production facilities on board. Using this type of storage system, produced hydrocarbons from a production platform **22** are transferred to an FSO vessel **26** via a flowline (not shown) extending from the production platform **22** to the FSO system **20**. Hydrocarbons transferred to the FSO vessel **26** are stored, typically in the hull of

the FSO vessel **26**. From the FSO vessel **26**, produced hydrocarbons are periodically offloaded onto a shuttle tanker **24** for transport to shore. Also, during periods when a shuttle tanker **24** is not available for offloading the storage facility on the FSO vessel **26**, it may become full requiring interruption of production until a shuttle tanker **24** is available.

[0009] Figure 2C is an illustration of a Direct Shuttle Loading (DSL) system **30**. In a DSL system **30** hydrocarbons produced from sub-sea wells **33** are collected at an offshore production gathering system, in this case a production platform **32**, and directly offloaded onto a shuttle tanker **34, 38** when available, through a flowline **36**. For the DSL system shown in Figure 2C, hydrocarbons are loaded onto one shuttle tanker **34** for transport to shore while another shuttle tanker **38** waits nearby for subsequent offloading after the first tanker **34** is full and en route to shore. Like other tanker-based storage systems described above, production operations which use DSL systems **30** are susceptible to interruptions in production due to severe weather conditions and periods of shuttle tanker unavailability. Additionally, the use of a DSL system **30** may require operation of a larger shuttle tanker fleet because the presence of at least one shuttle tanker **34, 38** is required at substantially all times in order for production operations to continue. Further, in cases where no temporary storage is provided at the production site, hydrocarbon production will be interrupted every time a shuttle tanker **34, 38** is connected or disconnected for offloading and transport.

[0010] Production platforms have also been developed to integrate oil storage into the hull **44** of a platform, such as a SPAR platform **40** as shown in Figure 2D. Thus, frequent tanker hook-ups to the platform **40** are required. In such cases, even a system comprising a platform **40** with integral storage is still too dependent upon the presence of a shuttle tanker **42**.

[0011] Other offshore storage systems for deepwater applications may also include smaller thick-walled tanks designed to be sunk to the seabed and internally controlled from the surface. Because the interiors of these tanks are completely isolated from the surrounding seawater environment, these tanks require very thick walls to withstand the hydrostatic pressure difference between the sub-sea environment and the platform environment. As a result, these systems are expensive and limited in capacity. These systems also require additional equipment such as pumps, controls, and other instrumentation, for monitoring and controlling the internal tank environment and moving fluids in and out of the tanks. Other offshore storage systems exist for use in shallow water applications; however, for the most part, these systems are not applicable for use in deepwater applications.

[0012] Natural gas produced from offshore gas and oil fields may be handled using a variety of mechanisms. For example, the natural gas may be re-injected into a subsurface formation, flared onsite, or exported by pipeline. Such mechanisms for handling natural gas is used in the industry in such locations as offshore of Nigeria, and in the North Sea. Alternatively, the natural gas obtained from a sub-sea well may be pressurized, to obtain high-pressure gas, and then transferred to a tanker in compressed form.

[0013] Figure 3 shows a system for offshore production of Liquefied Natural Gas (LNG). Natural gas supplied from an underground natural gas source **60** to a field installation **62** located on or adjacent to the sea bed **64**. The natural gas is treated by the field installation **62** and transferred in compressed form via a pipeline **66** to an LNG tanker **68**. The pipeline **66** through which the compressed natural gas flows is surrounded by sea water and supported by a submerged buoy **70** and a hawser **72**. The submerged buoy **70** is arranged for introduction and releaseable securement in a submerged, downwardly open receiving space in the LNG tanker

68. Aboard the LNG tanker **68**, the compressed natural gas is converted, at least partially, to LNG by liquefaction by a conversion plant **74**. The LNG is stored in storage tanks **76**. When the storage tanks **76** are full, the pipeline **66** is disconnected, and connected to another, similar, tanker.

[0014] An FPSO may also be used to obtain natural gas and liquefy the natural gas to produce LNG. The FPSO includes buffer storage tanks for temporary storage of continuously produced LNG during absence of an LNG tanker. Once the LNG tanker has returned, the LNG is offloaded from the FPSO to storage tanks on the LNG tanker using a mooring device and a cryogenic transfer device.

Summary of the Invention

[0015] In general, in one aspect, the invention relates to a method for developing a sub-sea hydrocarbons field. The method comprises liquefying natural gas aboard a vessel using liquid nitrogen aboard the vessel to obtain liquefied natural gas, transporting the liquefied natural gas to an onshore terminal, re-gasifying the liquefied natural gas, and obtaining a new batch of liquid nitrogen using energy recovered from re-gasifying the liquefied natural gas.

[0016] In general, in one aspect, the invention relates to a system for developing an oil and gas field. The system comprises a vessel configured to liquefy natural gas to obtain liquefied natural gas using liquid nitrogen aboard the vessel, and an onshore terminal configured to obtain a new batch of liquid nitrogen using refrigeration recovered from re-gasifying the liquefied natural gas.

[0017] In general, in one aspect, the invention relates to an apparatus for developing a sub-sea hydrocarbons field. The method includes means for liquefying natural gas aboard a vessel using liquid nitrogen aboard the vessel to obtain liquefied natural gas, means for transporting the liquefied natural gas to an

onshore terminal, re-gasifying the liquefied natural gas, and means for obtaining a new batch of liquid nitrogen using energy recovered from the re-gasifying the liquefied natural gas.

[0018] Other aspects and advantages of the invention will be apparent from the following description and the appended claims.

Brief Description of the Drawings

[0019] Figure 1 shows a prior art offshore production platform with processing and storage equipment on the platform.

[0020] Figure 2A is an illustration of a prior art Floating Production, Storage, and Offloading systems.

[0021] Figure 2B is an illustration of a prior art Floating Storage and Offloading system.

[0022] Figure 2C is an illustration of a prior art Direct Shuttle Loading system.

[0023] Figure 2D shows a prior art SPAR platform with an integral storage facility.

[0024] Figure 3 shows a system for offshore production of Liquefied Natural Gas (LNG).

[0025] Figure 4 shows an embodiment of a seabed oil storage and offtake system in accordance with the present invention.

[0026] Figure 5 shows an embodiment of a seabed oil storage and offtake system configured to supply production to a shuttle tanker.

[0027] Figure 6 is an illustration of an embodiment of a seabed oil storage and offtake system in oil fill mode.

[0028] Figure 7 is an illustration of an embodiment of a seabed oil storage and offtake system in oil offtake mode.

[0029] Figure 8 shows an embodiment of a seabed oil storage and offtake system used in connection with a sub-sea processing system.

[0030] Figure 9 shows an embodiment of a seabed oil storage and offtake system used in connection with a sub-sea processing system.

[0031] Figure 10 shows an embodiment of a system for developing an offshore oil and gas field.

[0032] Figure 11 shows an embodiment of a Floating Production Storage Shuttle Vessel (FPSSV) LNG Production Facility using LIN to provide the necessary refrigeration.

[0033] Figure 12 shows an embodiment of an onshore LNG re-gasification and Liquid Nitrogen (LIN) production facility using LIN to provide the necessary refrigeration.

[0034] Figure 13 shows an embodiment of a flowchart for developing a sub-sea oil and gas field.

Detailed Description

[0035] Referring to the drawings wherein like reference characters are used for like parts throughout the several views, Figure 4 shows one embodiment of a seabed pertains subsea storage hydrocarbon storage and offtake system in accordance with the present invention. The storage and offtake system comprises a storage tank **100** adapted for placement on and, possibly, attachment to, the seabed **114**. The tank **100** comprises a top **100a**, a bottom **100b**, and one or more side walls **100c**. At the base of the tank **100**, there is an amount of fixed ballast, such as sand, concrete or other dense material, to provide submerged weight to overcome

the buoyancy force of the hydrocarbon when the tank **100** is filled to its maximum storage capacity. In the embodiment shown, the tank **100** rests on the sea floor at a depth of approximately 6000 feet.

[0036] The tank may comprise any configuration as determined by one skilled in the art, including cylindrical-shaped, box-shaped, or the like. Those skilled in the art will appreciate that the configuration of the tank is a matter of convenience for the system designer. For example, in a particular embodiment, the tank may comprise a box-shaped configuration and a web-framed steel structure so that it may be constructed using standard ship building techniques, launched from conventional shipways, and have stable floatation for open-water tow.

[0037] The storage and offtake system further includes at least one fluid channel **127,** such as a standpipe more distinctly illustrated in Figures 5 and 6. As shown in the embodiment in Figures 5 and 6, the fluid channel **127** has a first end **124a** positioned inside of the tank **100** proximal the bottom **100b** of the tank **100** and a second end **124b** in fluid communication with the environment **125** outside of the tank **100**. In one or more embodiments, the second end **124b** is positioned away from the seabed (**114** in Figure 4).

[0038] Referring once again to Figure 4, the storage and offtake system further includes at least one offload comprised of a rigid riser **104** and a flexible hose **103**. The rigid riser **104** has a first end coupled to the tank **100** and in fluid communication with the interior of the tank **100** proximal the top **100a** of the tank **100**. A second end of the rigid riser **104** is connected to the flexible hose **103,** which adapted to couple in fluid communication to a transport vessel (illustrated in Figure 5) and to be accessible, in a manner, which will be further explained, from the water surface **116**.

[0039] The storage and offtake system further includes a vessel mooring system, which has at least one hawser **110**. As shown in Figure 4, the hawser **110** includes a first end operatively coupled to the surface buoy **106** and a second end adapted to be accessible from the water surface **116** through the surface buoy **112**. The second end is also adapted to attach to the transport vessel to anchor the transport vessel during offloading operations, as illustrated in Figure 5.

[0040] Referring once again to Figure 4, suction or conventional piles **102** may be used to attach the tank **100** to the seabed **114** to provide lateral resistance for the tank **100** to sliding due to the slope of the seabed or other lateral forces that may be applied to the storage tank **100** during operation. Additionally, the piles **102** may also act as a restraint for the storage tank **100**, which provides mooring for the tanker during offloading operations (illustrated in Figure 5).

[0041] It should be understood that the storage tank **100** may include any material suitable for use as a tank, *e.g.*, steel, concrete, or a composite material such as glass or carbon fiber reinforced plastic. The inside and outside of the tank **100** may also be coated with cement or any other coating material known in the art for protecting structures formed from a metal such as steel against deterioration due to operation in a saltwater environment. In one or more embodiments, the storage tank **100** is a gravity based, pressure balanced structure, as will be described in more detail below.

[0042] The lower portion of the offload line **103** in the embodiment shown includes a substantially rigid member, such as a marine riser **104**. As shown in Figures 3 and 4, the riser **104** in this embodiment is a self-standing, top-tensioned riser; wherein one end of the riser **104** connects to the top of the storage tank **100** and the other end of the riser **104** connects to a subsurface buoyant device (for example, subsurface buoy **106**) to maintain the riser **104** in tension in a substantially upright position when the system is submerged in water. To

facilitate the interface between the lower end of the riser **104** and the top of the tank **100a**, a Lower Marine Riser Package (LMRP) may be used, such as one available from ABB Vetco-Gray, Houston, Texas, or a similar device.

[0043] In one or more embodiments, the riser **104** also functions as part of the transport vessel mooring system (further described below). In such case, the riser **104** should be designed to withstand the additional forces expected to be imposed on it by mooring a tanker (illustrated in Figure 5) to the tank **100** via the riser **104**. Those skilled in the art will appreciate that the riser **104**, or the like, may be made of any material suitable for the particular application, *e.g.*, steel, or a composite material. Additionally, the external surface of the riser **104** exposed to the seawater environment may be coated with a suitable protective material.

[0044] As previously described and shown in Figure 4, a subsurface buoy **106**, or other buoyant device, may be attached to the upper end of the riser **104** to maintain the riser **104** in an upright position and in tension. For example, the subsurface buoy **106** illustrated in Figure 4 may include one or more chambers filled with fluid substantially lighter than seawater, such as air or oil, and a center passage therethrough for the top of the riser **104** to interface with an end of the upper portion of the offload line **103**.

[0045] Also as shown in Figure 4, the subsurface buoy **106** and the upper end of the riser **104** are located a selected distance below the water surface **116**. This distance may be selected such that the effects of surface environmental loads, such as the wind, waves, and current, on the subsurface buoy **106** and riser **104** will be feasibly minimized. A desirable depth for a particular embodiment is site specific and may be determined by one skilled in the art based on factors such as the structural integrity of a selected riser **104** (e.g., rigidity, length, and tension) and worst case environmental operating conditions, such as a 1-year, 10-year, or 100-year worst storm criteria for the particular sea state. For example, based on the

structural integrity of a particular riser and particular storm criteria, a subsurface buoyant device may be located at a depth below the water surface such that the effects of waves and surface currents on the buoyant device is less than 10%, or more preferably less than 2%, of the effect if the buoyant device was located at the water surface **116**. In some cases this depth may be at least 50 feet below the water surface **116**. In other cases this depth may be at least 200 feet below the water surface **116**. However, as will be appreciated by those skilled in the art, criteria used to determine the desired depth of the subsurface buoyant device and the selected depth are matters of convenience for a system designer. Further, those skilled in the art will appreciate that in the case of the riser **104** used as part of the mooring system (further described below), the tension needed on the riser can be determined based on factors such as the size of the shuttle tanker to be moored, the water depth in which the system is installed, environmental conditions (such as wind, waves, and current) at the particular site, and the worst storm conditions for which the system is designed to function.

[0046] The upper portion of the offload line **103** may include a flexible member, such as a hose or series of rigid segments (*e.g.*, subpipe sections) coupled by flex joints. In the embodiment shown in Figures 3 and 4, the flexible member includes a hose **108**. The hose **108** provides a flexible fluid channel, which extends from the top of the riser **104** to the water surface **116**. The hose **108** is in fluid communication with the riser **104** through the subsurface buoy **106** to transfer hydrocarbons (oil) from the tank **100** to a transport vessel such as a shuttle tanker (shown as **113** in Figure 5) or the like.

[0047] In the embodiment shown, the lower end of the hose **108** is attached to the top of the riser **104** at the subsurface buoy **106**, and the upper end of the hose **108** is attached to a surface buoy **112** so that the hose **108** can be easily accessed from the water surface **116** for offloading (or offtake) operations. Those skilled in the

art will appreciate that the flexible upper portion of the offload line **103** may be made of any material suitable for a particular application, such as rubber, metal, composite material, or a combination thereof.

[0048] As shown in Figures 3 and 4, in one embodiment, the hawser **110** operatively couples to the tank **100** through the riser **104**. One end of the hawser **110** is connected to the subsurface buoy **106** at the upper end of the riser **104**. The other end of the hawser **110** is connected to the surface buoy **112**. As a result, the hawser **110** can be used to anchor a transport vessel, such as a shuttle tanker (**113** in Figure 5) or the like, to the tank **100** during offloading operations, or during servicing of the system. In this embodiment, the hawser **110** is shorter in length than the hose **108**, which ensures that the hawser **110**, and not the hose **108**, provides the anchoring connection between the riser **104** and any vessel connected to the hawser **110** at the water surface **116**. Those skilled in the art will appreciate that in other embodiments, the hawser **110** may be operatively coupled directly or indirectly to the tank **100** in a manner different than the manner shown in Figures 3 and 4, without departing from the spirit of the invention. Those skilled in the art will also appreciate that hawsers for mooring transport vessels and the like are well known in the art and that any type of hawser considered suitable for a particular application by a system designer may be used for the system without departing from the spirit of the invention.

[0049] As previously explained with respect to Figure 4, one or more buoyant devices, such as surface buoy **112**, may be attached to the upper end of the hose **108** and the upper end of the hawser **110** to maintain the surface ends thereof so that they are easily accessible at the water surface **116**. In some embodiments, the storage and offtake system may also include a coupling, such as a flex joint **118** and/or swivel joint **120**, disposed between the riser **104** and the hose **108** and/or the riser **104** and the hawser **110** to enable the hose **108** and the hawser **110** to

rotate freely with respect to the riser **104**. In the embodiment shown in Figure 4, the flex joint **118** is positioned between the riser **104** and the subsurface buoy **106**, and a swivel joint **120** is positioned between the top of the riser **104** and the ends of the hose **108** and hawser **110** proximal the subsurface buoy **106**. Additionally, the system may include any connection device known in the art at the accessible end of each of the hose **108** and the hawser **110** for releasably connecting the hose **108** and the hawser **110** to a tanker **113** or other transport vessel during offloading operations.

[0050] Now referring to Figures 6 and 7, as previously discussed, the storage tank **100** of the system is substantially pressure balanced. This pressure balance can be achieved by providing that the inside of the tank **100** is in fluid communication with the seawater environment outside of the tank **100** at substantially the same depth. Those skilled in the art will appreciate that in the case of a pressure balanced tank **100**, the transportation and installation loads, rather than differential pressure across the tank **100** during operation will primarily affect the structural design of the tank **100**. This allows for pressure balanced tanks to have substantially reduced wall thickness in comparison to enclosed storage systems on the seabed, which are subject to hydrostatic pressure differences across the walls of the tank. This also allows for feasible tanks with larger storage capacities, such as up to 2 million barrels of oil, for deepwater service, such as in depths up to 10,000 feet of water, or more. In one embodiment, for example, the tank may have dimensions of about 200 feet long, about 200 feet wide, and about 150 feet tall and may have a capacity around 750,000 barrels. Thus, embodiments of the invention may provide a lower cost option and/or increased storage capacity than other storage systems.

[0051] Examples of a pressure balanced tank during normal operations in accordance with the above description are shown in Figures 6 and 7. Figure 7 is

an illustration of a storage tank **100** during a "filling" operation. Figure 7 is an illustration of a storage tank **100** during an "offtake" operation. In the examples shown, the pressure balance is achieved through the use of a fluid channel **127**, which extends from a lower location inside of the storage tank **100** through an upper section of the tank **100** and into the surrounding seawater environment **125**. The fluid channel **127** allows the interior of the storage tank **100** to be in fluid communication with the seawater environment **125**. Hydrocarbons **121** entering the tank **100** will float to the top **100a** of the tank **100** and become trapped in the riser **104** and the upper portion of the tank **100**, thereby displacing water **123** in the tank to the bottom **100b** of the tank **100**.

[0052] Those skilled in the art will appreciate that the tank **100** may additionally include instrumentation to ensure that the maximum and minimum oil **121** and water **123** levels for a selected tank design are not exceeded. Those skilled in the art will also appreciate that the fluid channel **127** may be constructed in any configuration and may communicate with the seawater environment outside of the tank **100** at any location, such as through a side wall of the tank **100**, as determined by the system designer without departing from the spirit of the invention. In one embodiment, the fluid channel **127** is in fluid communication with the surrounding seawater environment **125** at a location away from the seabed (**114** in Figure 4 and 5) as further discussed below.

[0053] As shown in Figure 6 (and Figure 7), the fluid channel **127** may extend through the top of the tank **100** to elevate the point of water discharge (and intake) at the external end **124b** of the fluid channel **127**, away from the seabed (at **114** in Figures 4 and 5). Locating the external end **124b** of the fluid channel **127** away from the seabed (**114** in Figures 4 and 5) improves the dispersion of seawater exiting the tank and prevents scouring around the base of the storage tank **100**. A storage tank **100** with a fluid channel **127** as shown in Figures 6 and 7 is

functionally the same as an opened bottom tank with respect to pressure-balancing the tank. However, a storage tank **100** with a fluid channel **127** for seawater intake and discharge is more effective because it eliminates problems associated with water dispersion and scouring around the base of the tank **100**. Additionally, a storage tank **100** having a fluid channel **127** arrangement as shown may also allow for improved monitoring and control of seawater flow in and out of the storage tank **100** in comparison to open bottom tanks. For example, the system may additionally include instrumentation in or proximal to an end of the fluid channel **127** for monitoring and controlling fluid flow through the fluid channel **127** as determined by the system designer. For instance, a device measuring the resistivity of fluids or residue oil content in the water leaving the fluid channel **127** may be included in the system.

[0054] Referring to Figure 6, during production operations, as hydrocarbons enter the storage tank **100** through the inlet **122**, the hydrocarbon/water interface **129** is pushed downward displacing seawater **123** out of the fluid channel **127** and into the surrounding seawater environment **125**. It should be understood that in one embodiment, this hydrocarbon/water interface **129** is naturally formed by pumping hydrocarbons (oil) **121** directly on water **123** in the tank and allowing the hydrocarbons **121** to naturally rise to the top of the tank **100** displacing water **123** to the lower section of the tank **100**. However, in other embodiments this interface **129** may be mechanically maintained using a flexible or permeable membrane member in the tank, which is displaced in the tank as hydrocarbons **121** flow in or out of the tank **100**.

[0055] Referring now to Figure 7, during offtake operations, hydrocarbons **121** in the tank **100** may be offloaded onto a transport vessel, such as a shuttle tanker (**113** in Figure 5) or the like for transport to shore. For example, once the transport vessel is moored using the hawser **110** (in Figure 5), and the hose **108** (in Figure

5) is connected to the vessel, a surface valve or other remotely located valve, such as valve **128**, is opened and the hydrostatic pressure imbalance due to the gravity difference between the hydrocarbon and seawater columns provides the motive force required to force the hydrocarbons **121** up the riser **104** and hose **108** (in Figure 5) to the transport vessel at the surface **116**. Thus, no pump is required to lift the hydrocarbons **121** from the storage tank **100** to the shuttle tanker (**113** in Figure 5) during the offtake operation. The energy available to transport hydrocarbons **121** up the offload line **103** (in Figure 5) is substantially equal to the hydrostatic pressure difference between the hydrocarbons **121** and seawater **123** columns. For example, for a 30° API oil stored in a tank at a 6,000-foot water depth, the differential pressure between the fluid columns will be about 325 psi, which is more than sufficient to move the hydrocarbons **121** up the offload line **103** (in Figure 5) and into a tanker **113**.

[0056] Now referring again to Figure 4, one skilled in the art will appreciate that to install a storage tank **100** at a location offshore, the tank **100** may be filled with a fluid lighter than seawater, such as light oil, in protective water and towed to a desired location. Seawater may then be pumped into the tank **100** while displacing the light oil to sink the tank **100** to the seabed **114**. The displaced light oil may be recovered and stored in an accompanying tank or tanker. For example, once at the desired surface location, seawater may be pumped into the inlet **122** of the tank **100** until the weight of the seawater plus the weight of the tank **100** is sufficient to overcome the buoyancy force on the tank **100**, which initially is full of light oil. Once the buoyancy of the tank **100** is properly adjusted with light oil and seawater, tank **100** is lowered to the seabed. Then, when the tank **100** is in place on the seabed **114**, the piles **102** around the tank **100** are installed and the offload line **103**, the inlet lines (at **122**), and the remaining system components are connected to the tank **100**.

[0057] Embodiments of a storage and offtake system may be used in conjunction with a sub-sea processing and/or gathering system as illustrated in Figures 8 and 9. For example, referring to Figure 9, the sub-sea processing system may comprise a sub-sea oil and gas separator **136** for degassing liquid hydrocarbons produced from the sub-sea wells **132** (in Figure 8). An example of a sub-sea processing system is described in U.S. Patent No. 6,537,349, issued on March 25, 2003, entitled "Passive Low Pressure Flash Gas Compression System," and incorporated herein by reference. As shown in Figure 9, when an embodiment of the invention is used with a sub-sea processing system, gas **134** separated from the liquid hydrocarbons may be routed to a gas handling system and the liquid hydrocarbons (oil) **121**, exiting the separator **136** at a lower pressure can then be pumped via oil transfer pumps **135** into the inlet **122** of the tank **100**.

[0058] A system for developing an offshore oil and gas field is shown in Figure 10. A sub-sea separator **136** obtains hydrocarbons from one or more sub-sea wells **132**. In accordance with one embodiment of the invention, the sub-sea separator **136** includes a two-phase separator (gas and liquid). In accordance with another embodiment of the invention, the sub-sea separator **136** includes a three-phase separator (gas, oil, and water). The sub-sea separator **136** de-gasifies the hydrocarbons, thus generating natural gas and oil. In accordance with one embodiment of the invention, the oil is partially stabilized. The oil is output to the storage tank **100** (in Figure 4). Those having ordinary skill in the art will recognize that the description of a two or three phase separation is not intended to limit the scope of the present invention and that different types of phase separators may be used.

[0059] Sub-sea flow lines **180** convey the natural gas output from the sub-sea separator **136** to a vessel, such as a Floating Production Storage Shuttle Vessel (FPSSV) **182** using a natural gas conveyance system, which includes a riser **184**, a

hose **188**, a hawser **190**, a subsurface buoyant device **192**, a flex joint **194**, a swivel joint **196**, and a sub-sea flow line-to-riser adapter **197**. The riser **184**, the offload line **186**, the hose **188**, the hawser **190**, the subsurface buoyant device **192**, the flex joint **194**, and the swivel joint **196** function similarly, and have properties similar to, the riser **104**, the hose **108**, the hawser **110**, the subsurface buoyant device **106**, the flex joint **118**, and the swivel joint **120** shown in Figures 3-4 and 7-10.

[0060] In accordance with one embodiment of the invention, the riser **184** is a top-tensioned riser used in conjunction with a flexible hose (*i.e.*, a "hybrid riser"). In accordance with one embodiment of the invention, the riser **184** is a steel catenary riser. In accordance with one embodiment of the invention, the riser **184** is a flexible pipe. In accordance with another embodiment of the invention, natural gas conveyed to the FPSSV **182** is not compressed, *i.e.*, is low-pressure gas.

[0061] A power and control buoy **198** provides electric power and control functions to the sub-sea separator **136** and sub-sea oil wells **132**. Examples of the power and control buoy **198**, in accordance with embodiments of the invention, may include the Sea Commander Buoy developed and marketed by Resource Technology Development Ltd. Functionality of the power and control buoy **198** may be similar to the buoy used in Western Australia for the East Spar Alliance, except with greater electrical capacity.

[0062] In accordance with one embodiment of the invention, the FPSSV **182** may provide electric power and control functions to the sub-sea separator **136** and sub-sea oil wells **132**. Other types of buoy backup systems may be used to provide electric power and control functions to the sub-sea separator **136** and sub-sea oil wells **132**, in accordance with embodiments of the invention.

[0063] Natural gas conveyed from the sub-sea separator **136** to the FPSSV **182** is liquefied aboard the FPSSV **182** to obtain Liquefied Natural Gas (LNG). An FPSSV LNG Production Facility **200** is used to liquefy the LNG. The FPSSV **182** transports the LNG to an onshore terminal **202**. In accordance with one embodiment of the invention, the onshore terminal **202** may not necessarily be on dry land, but may be in close proximity to dry land, *e.g.*, on a platform located in the proximity of shore. The use of more than one FPSSV **182** may be facilitated by use of a second riser **204**, a second hose **208**, a second hawser **210**, a second subsurface buoyant device **212**, a second flex joint **214**, a second swivel joint **216**, a second sub-sea flow line-to-riser adapter **218**, and a surface buoy **219**. The surface buoy **219** has functionality and properties similar to the surface buoy **112** in Figure 4.

[0064] Figure 11 shows the FPSSV LNG Production Facility **200**, which is located aboard the FPSSV **182** (in Figure 10). A natural gas liquefaction plant **222** takes a pre-treated natural gas input **224** from a natural gas pre-treating facility **226**, which takes in natural gas **228** from the flexible hose **188** (in Figure 10). The natural gas pre-treating facility **226** removes contaminants, such as water vapor, carbon dioxide, hydrogen sulfide, mercury, etc.

[0065] In accordance with one embodiment of the invention, the natural gas liquefaction plant **222** uses an open-cycle, open loop process, and takes Liquid Nitrogen (LIN) as an input from one or more FPSSV storage tanks **230** via one or more pumps **232**. LIN vaporized during liquefaction is vented as nitrogen gas (N2) via a nitrogen vent **234**. LNG created during the natural gas liquefaction process is stored in FPSSV storage tanks **230** aboard the FPSSV.

[0066] The LNG stored in the FPSSV storage tanks **230** is transported aboard the FPSSV to the onshore terminal. In accordance with one embodiment of the invention, the onshore terminal **202** (in Figure 10) may not necessarily be located

on dry land, but may be in close proximity to dry land, *e.g.*, on a platform located in the proximity of shore. The LNG is transferred to the Onshore Terminal Storage tanks.

[0067] Figure 12 shows an onshore LNG re-gasification and LIN production facility **260**. LNG input **262** from the Onshore Terminal storage tanks **230** is input to a pump **264**, which outputs High Pressure (HP) LNG **266**. The HP LNG **266** is input to an LNG vaporizer **268**. In accordance with one embodiment of the invention, the LNG vaporizer **268** may operate in a manner consistent with conventional LNG vaporizers, as known to those skilled in the art. The LNG vaporizer **268** outputs High Pressure (HP) natural gas **274**. In a conventional operation, the LNG vaporizer **268** may take warm seawater from input **270** and discharge cold seawater output from **272**. The LNG vaporizer **268** may also include a heat input **273**. However, according to embodiments of the invention, the LNG vaporizer **268** is used in conjunction with an integrated LNG re-gasification air separation plant **276** so that the refrigeration from re-gasification of HP LNG **266** may be used to generate LIN.

[0068] In order to recover energy from re-gasification of the HP LNG **266**, all or a portion of the HP LNG input **266** is input to the integrated LNG re-gasification air separation plant **276**. The integrated LNG re-gasification air separation plant **276** takes as input air **278** compressed by a compressor **280**. An output of the integrated LNG re-gasification air separation plant **276** is LIN **282**, which is transferred to the FPPSV **182** (in Figure 10), and stored in FPSSV storage tanks **230**. In accordance with one embodiment of the invention, one FPSSV storage tank **230** of the FPSSV may be empty when the FPSSV transports the LIN **282** offshore, and additional FPSSV storage tanks **230** will become available when LIG is revaporized.

[0069] A flowchart for developing a sub-sea oil and gas field is shown in Figure 13. A first operation of the flowchart is obtaining natural gas and partially stabilized oil by de-gasifying the hydrocarbons obtained from the sub-sea wells **Step 300**. Then, once natural gas has been obtained from the hydrocarbons, the natural gas is conveyed to a vessel, such as the FPSSV **(Step 302)**, and the oil is stored in the storage tank **(Step 304)**. The oil is partially stabilized after natural gas has been separated. The natural gas is conveyed to the FPSSV via the sub-sea flow lines and riser, as shown in Figure 10.

[0070] Once the natural gas is aboard the FPSSV, the natural gas is liquefied using LIN stored aboard the FPSSV to obtain LNG **(Step 306)**. The LNG is stored in the FPSSV storage tanks and transported to the onshore terminal **(Step 308)**. At the onshore terminal, the LNG is re-gasified to obtain HP gas and recovered refrigeration, which is used to produce LIN **(Step 310)**. The LIN is then loaded into the FPSSV storage tanks and transported to the offshore oil field **(Step 312)**. In accordance with one embodiment of the invention, one of the FPSSV storage tanks is left empty, and the LIN is transported in the remaining FPSSV storage tanks. In accordance with one embodiment of the invention, some of the FPSSV storage tanks may hold LIN that is not produced using recovered energy, but has been obtained from another source other than the LNG re-gasification LIN production facility (shown as **260** in Figure 12).

[0071] Once the FPSSV is at the location of the offshore oil field, more natural gas is conveyed aboard the FPSSV **(Step 314)**, and the natural gas is liquefied aboard the FPSSV using the onboard LIN to obtain more LNG **(Step 316)**. An initial quantity of LNG obtained using the LIN is stored in the empty FPSSV storage tank. Subsequent quantities of LNG obtained using the LIN are stored in the FPSSV storage tanks that are emptied as the LIN is used in the liquefaction process. Oil (*e.g.*, partially stabilized oil) is offloaded from the oil tank on the

seabed onto a tanker periodically **(Step 318)**. Steps 308-316 are repeated to the gas/LNG while the sub-sea oil and gas field is in operation; as is step **318** for the oil.

[0072] Embodiments of the invention may also be used to eliminate the need for costly deepwater pipelines to shore, and in some cases may be used to avoid expensive pipeline tariffs. Embodiments of the invention may be operated independent of infrastructure, such as pipelines. Embodiments of the invention may also provide larger storage capacity for offshore production sites in deepwater that is less costly to operate and maintain than prior art storage systems primarily dependent upon shuttle tankers or submerged thick walled storage vessels. Embodiments of the invention may also be used to reduce the number of shuttle tankers required in a hydrocarbon transport fleet. Embodiments of the invention may also provide cost reductions for development of sub-sea oil and gas fields.

[0073] The above advantages are merely exemplary of advantages that may be associated with one or more embodiments of the invention. Those skilled in the art will appreciate other advantages. Further, while the invention has been described with respect to a limited number of embodiments, those skilled in the art will appreciate that other embodiments can be devised which do not depart from the scope of the invention as disclosed. Accordingly, the scope of the invention should be limited only by the attached claims.